Lasers in Surgery and Medicine 19:324–330 (1996)

Pulsed Erbium:YAG Laser Ablation in Cutaneous Surgery

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Background and objective: **Among the various pulsed midinfrared-lasers studied in skin surgery the 2.94 μm Erbium:YAG laser has been shown to combine most efficacious ablation with least thermal damage due to its unique absorption characteristics in tissue water.**
A newly developed high-power Erbium:YAG laboratory laser providing output energies (up to 1.5 J/pulse) and repetition rates (up to 15 Hz) appropriate for clinical use enabled us to investigate its potential indications in dermatological surgery.
Study Design/Materials and Methods: **Erbium:YAG laser ablation was performed in vitro on pig skin and in vivo on a total of 30 patients presenting with different skin disorders.**
Results: **In vitro ablation efficiency linearly increased with radiant exposure and was inversely correlated with pulse frequency. Ablation rate at 10 Jcm^{-2} (used clinically) measured from ~10 μm (at 10 Hz) to 40 μm (at 1 Hz). Also for high repetition rates thermal necrosis did not exceed 50 μm, corresponding clinically to capillary bleeding after exposure of the dermis. Superficial lesions, such as epidermal nevi, were easily ablated and re-epithelization was unimpaired owing to the absence of tissue necrosis. In tattoos, exposed pigment particles were precisely removed. However, in deeper lesions the casual onset of bleeding impeded the procedure and scar formation was observed after reepithelization.**
Conclusion: **Pulsed 2.94 μm Erbium:YAG laser surgery allows an extremely precise etching of delicate superficial skin lesions and also should have a potential for skin resurfacing.**

Key words: **Erbium:YAG laser, skin ablation, tattoos, epidermal nevi**

INTRODUCTION

Within recent years growing interest has focused on the clinical use of pulsed laser systems in dermatology to avoid thermal side effects [1]. Apart from the concept of using pulsed systems to treat pigmented or vascular lesions by selective photothermolysis [2], pulsed laser light sources also have been developed for surface ablation purposes. Whereas continuous wave laser vaporization is frequently associated with tissue carbonization and coagulation, the use of pulsed laser systems for superficial skin etching aims at a minimization of adjacent thermal injury [3].

Various laser types have been studied for skin ablative properties, including ultraviolet-excimer-, pulsed CO_2-, Holmium-, Thulium-, Er:YSSG-, and Erbium:YAG lasers, respectively [4–12]. Among these, pulsed and flashscanned CO_2 systems have recently been shown to reduce thermal side effects and hence were clinically applied for delicate superficial procedures, such as resurfacing of scars or sun-damaged skin [4,5].

Accepted for publication October 5, 1995.

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Part of this work was presented at the 15th annual meeting of the American Society for Laser Medicine and Surgery, April 1995, San Diego, CA.

The newly introduced ultrapulse CO_2 laser has a pulse duration of ~1 millisecond and a peak pulse power of ~500 Watts [5]. Even shorter pulses (~0.2 milliseconds) combined with up to tenfold higher pulse powers and increased laser light absorption in tissue water are provided by the Erbium:YAG system. These features suggest superior ablation characteristics with both efficacious tissue removal and least thermal injury, which has been confirmed by our earlier preliminary data [6,11–14]. Based on this work we now investigated a newly developed Erbium:YAG system providing output energies and repetition rates appropriate for clinical use. Besides its in vitro effects on pig skin, we also studied its potential indications in dermatological surgery.

SUBJECTS AND METHODS

Laser System

All treatments were carried out with a pulsed Erbium:YAG laser (laboratory system, Institut für Lasertechnologien in der Medizin und Meßtechnik, Ulm, Germany). Maximum output energy per pulse was 1.5 J. Pulse duration could be varied between 150–600 μs and repetition rate from 1–15 Hz. Pulse-to-pulse energy variation was <10%. Laser light was transmitted by an articulated arm and focused by a 100 mm INFRASIL-lens. Spatial beam profile at the focal plane was adjusted to a nearly top hat shape with a diameter of 1.0 mm or 2.0 mm, respectively. Ablated tissue debris was collected by a smoke evacuator (Limmer, Germany).

In Vitro Studies

For in vitro testing of different pulse parameters and repetition rates on tissue ablation and thermal damage, we obtained excessive pig skin fresh from slaughter. Samples were irradiated perpendicular to the surface with 10 pulses applied onto the same site. In all experiments, spot size was set to 2.0 mm. Three samples were evaluated each time. Pulse energies were tested at 300, 450, and 600 mJ with a total pulse duration of 150 and 450 μs, respectively. Repetition rates of 1, 5, and 10 Hz were used for each pulse energy. Tissue samples were prepared for standard histopathological examination (HE-stain). Depth and diameter of ablation craters were measured by an ocular micrometer. Surrounding coagulation necrosis as indicated by loss of collagen birefringence was quantified using polarization microscopy. Both average ablation rate and coagulation depth were calculated for each parameter setting.

TABLE 1. Patients and Treatment Characteristics

Diagnosis	No. patients	No. lesions	Spot size (mm)	Pulse energy (mJ)
Professional tattoos	5	8	2	315
Amateurish tattoos	2	2	2	315
Epidermal nevi	6	10	2	315
Adenoma sebaceum	3	multiple	2	315
Solitary angiofibroma	3	22	1	85
Syringoma	4	multiple	1	85
Xanthelasma	4	9	2	315
Sebaceous hyperplasia	2	7	1	85
Osteoma cutis	1	multiple	1	85

Patients

After ethical approval and written consent, a total of 30 patients (age 16–58 yr., 20 females, 10 males) presenting with different superficial skin disorders (Table 1) were included in this open trial. Local infiltration anesthesia (mepivacaine 1% with epinephrine 1:200.000) was given when required. Smaller lesions (e.g., syringoma) were ablated with a 1 mm beam diameter, whereas in more extensive lesions (e.g., tattoos), a 2 mm spot size was used. Repetition rates were adjusted to 10 Hz. Output energies varied between 85 and 315 mJ in order to obtain a radiant exposure of 10 ± 1 J/cm^2. This energy density was sufficient to achieve an efficacious etching of the skin surface under in vivo conditions, when combined with a 10 Hz repetitions rate. In all treatment sessions, total pulse numbers were recorded. In lesions larger then the spot size, the laser beam was moved in a meander-like fashion across the surface. For a stepwise ablation, several passes were required. Punctual lesions, however, were treated by multiple pulsing on the same spot. Postoperatively, smaller punctual defects were treated with an antiseptic ointment until reepithelisation was achieved; larger areas were protected by use of a sterile polyurethane membrane (Tegaderm®).

RESULTS

In Vitro Findings

Macroscopically the laser pulses created a clean crater exhibiting sharp margins without visible signs of tissue carbonization, even after multiple pulses were applied onto the same spot. Histological examination revealed a nearly rectangular lesion, corresponding to the beam profile

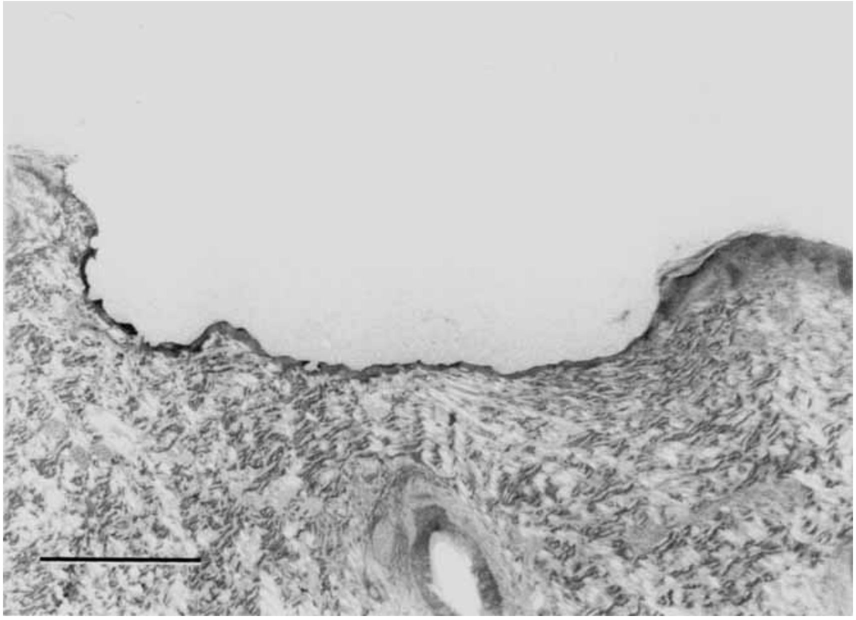

Fig. 1. Polarization microscopy of an in vitro crater lesion following Erbium:YAG ablation with 10 pulses at a repetition rate of 1 Hz and a pulse energy of 300 mJ. Only a narrow rim of adjacent tissue coagulation is evident. Bar = 500 μm.

(Fig. 1). The results of ocular micrometry are summarized in Figure 2a. The ablation rate per pulse was in the range of some 10 micrometers. It increased linearly with the radiant exposure and was also affected by the pulse repetition rate: for a given radiant exposure ablation efficacy decreased when pulse frequency was raised. However, pulse duration in the tested range (150 μs, 450 μs) revealed to be insignificant with respect to ablation rates.

Craters were entirely surrounded by a narrow rim of coagulation necrosis (Fig. 1), but never exhibited any signs of carbonization or vacuole formation. The extend of thermal damage increased only slightly with higher repetition rates, but never exceeded a depth of ~50 μm of collagen denaturation (Fig. 2b). In contrast, neither for energy nor for pulse duration any influence could be observed.

Treatment of Skin Lesions

Clinical application of Erbium:YAG laser pulses resulted in a clean ablation of epidermal and dermal structures. Each pulse produced a characteristic bang. No surface discoloration, carbonization, smoke formation or tissue shrinkage could be observed during the procedure. There was no need for cleansing the surface between subsequent laser passes. The ablated tissue debris was ejected from the wounded surface in tiny fluffs producing a white-colored tissue dust, which was collected by a smoke evacuator system. With deeper lesions onset of bleeding was observed due to a lack of relevant hemostasis. Ensuing capillary bleeding was wiped off by saline soaked compresses, while the ablation procedure was continued adjacently. With the exception of two cases (sebaceous hyperplasia), all patients required local anesthesia for relief of pain.

Seven tattoo patients were treated. Although a nearly 100% removal of the pigment was achieved, slightly atrophic scars developed, which were depigmented in five cases. In superficial tattoos (n = 5), the epidermal layer was removed stepwise in about two to three passes uncovering the reticular dermis. Pigment particles could be selectively removed after exposure of the appropriate dermal tissue plane in further steps. Reepithelization was achieved within 2–4 weeks depending on the ablated surface area and depth. Transitory postoperative erythema developed in all cases followed by slightly atrophic scars, three of which were depigmented. An average of 580 pulses was needed to ablate an area of 1 cm^2, corresponding to a total radiant energy of 182 kJ. In both cases presenting with deeper tattoos (blue-black amateurish lesions), the ablative procedure was now and then hampered after the onset of

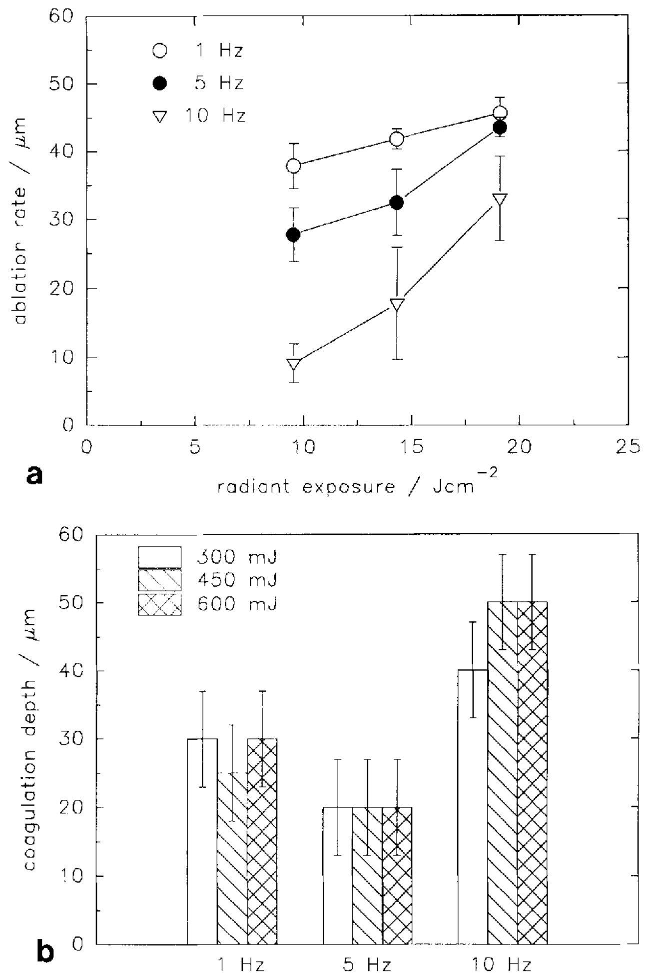

Fig. 2. (a) In vitro ablation rate on pig skin as a function of radiant exposure and pulse repetition rates. Ablation rate increases linearly with energy density and is inversely correlated with repetition rates. Clinically pulses of ~11 Jcm^{-2} were delivered at 10 Hz. (b) In vitro coagulation depth of ablation craters as a function of pulse repetition rates and pulse energy. With parameters used in clinical applications (10 Hz, 350 mJ, 2 mm spot size) no tissue carbonization or relevant coagulation was visible corresponding to in vitro coagulation zones not exceeding 50 µm.

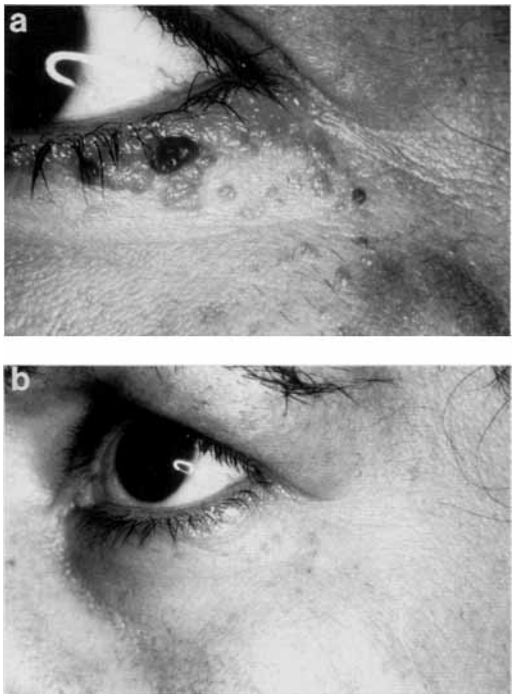

Fig. 3. (a) Preoperative appearance of an epidermal nevus, composed of aggregated papular lesions. (b) Result 6 weeks after the first treatment session with removal of all larger papules along the edge of the eyelid.

bleeding, especially when the particles were located down in the deeper reticular dermis along the subcutaneous border. However, bleeding could be controlled by intermittent application of saline soaked gauze compresses. Although ablation was continued meanwhile in adjacent areas, the need for hemostasis prolonged the procedure. Hypertrophic scarring was prevented by compression bandages, which were applied over a 3-month period after full reepithelization. Both patients developed hypopigmented slightly atrophic scarring.

Two out of six patients suffering from epidermal nevi had larger plaque-like lesions (Fig. 3), whereas the remainder presented with nevi composed of small aggregated papules (Fig. 4). All lesions were located in the face and neck area of light-colored caucasians. In all cases a superficial precise etching strictly confined to the lesional skin could be achieved. No residual scarring or relevant pigmentary changes were visible after a 6-month follow-up. One case developed few isolated miliae, which were removed by needle incisions.

Also, papular adnexal lesions such as sebaceous hyperplasias were stepwise removed by Erbium:YAG laser ablation and the remaining defects healed by secondary intention. Three patients presented with adenoma sebaceum and three further cases with angiofibromas not associated with Pringle disease. Lesion by lesion was ablated down to the middermis. Two cases with extensive Pringle disease had partial smoothening of the densely aggregated papules after one treatment session, whereas in isolated or scattered papules, transient erythema developed following secondary healing. After 3 months, no visible scar formation was noted and partial re-

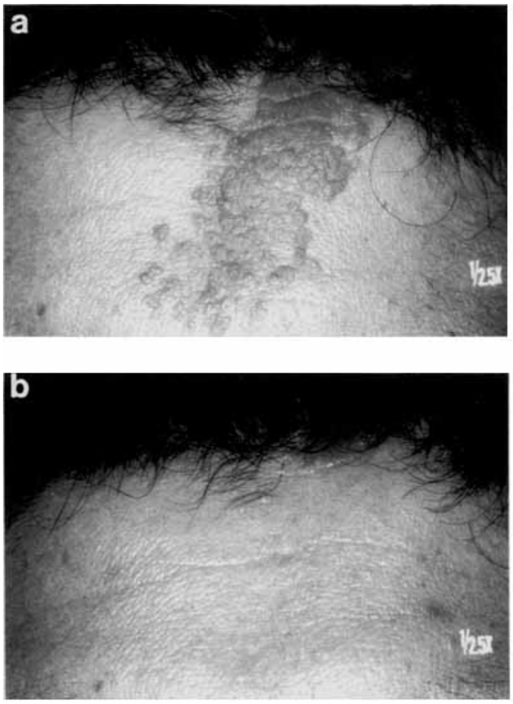

Fig. 4. Epidermal nevus, plaque-type lesion on the forehead. (**a**) Clinical appearance prior to treatment. (**b**) Outcome 6 months following Erbium:YAG laser ablation of the entire area.

Fig. 5. (**a**) Xanthelasma of the inner Canthus prior to treatment. (**b**) Outcome 8 weeks postoperatively.

currence of isolated lesions could be observed in one case.

Xanthelasmas of the eyelids were treated in four patients (Fig. 5). After stepwise removal of the skin surface the entire lesions were ablated in several passes down to the underlying uninvolved tissue. Capillary bleeding could be controlled after saline gauze application. No interfering hemorrhage was noted while ablating the exposed yellowish xanthelasma tissue. An antiseptic ointment was prescribed until reepithelization had been completed. Only in two larger xanthelasmas discrete atrophic scars were visible up to 4 months of follow-up.

In one case suffering from osteoma cutis of the face [15], we produced ablation craters, through which smaller bony particles could be expressed in toto. Larger particles were partially ablated or fragmented by the pulsed laser beam prior to removal, since the Erbium: YAG laser is also capable of etching hard substances such as bone, dentin, or enamel [16].

DISCUSSION

It is the special feature of the Erbium:YAG laser that its emission wavelength of 2.94 μm exactly matches the main peak of water absorption. The H_2O absorption coefficient is 12,800 cm^{-1} compared to 800 cm^{-1} for the 10.6 μm line of the CO_2 laser [17]. Considering a water content of 77 weight % (70 vol.%) in skin, its absorption coefficient can be estimated to be ~10,000 cm^{-1}, corresponding to an optical penetration depth of only 1 μm. This is more than one order of magnitude smaller than for the CO_2 laser. When the high power radiation of the pulsed Erbium:YAG laser, which is in the range of some kW, is focused onto skin, this results in a very rapid temperature increase within a thin surface layer, leading to explosive ablation, including the ejection of small tissue fragments. Although pulsed laser radiation is used, the Erbium:YAG laser ablation of tissue has been shown to be a continuous process beginning with a short delay after the onset of the pulse and lasting to its end [18,19]. As a consequence, a part of the early ablated material passes the incoming radiation.

Prior investigation on the quantitative amount of Erbium:YAG laser-induced skin removal [13,14] revealed a linear increase of the ablation rate with radiant exposure with a threshold of ~1 Jcm^{-2} and a slope efficiency of 6.7

$\mu m/Jcm^{-2}$. The corresponding ablation energy of 1.5 $kJcm^{-3}$ is lower than the energy required to vaporize the complete water content. This can be understood if humid fragments are ejected radially out of the beam path. From the results of the prior experiments, which were performed with a spot size of 1 mm in diameter and a repetition rate of 1 Hz, one would calculate for the radiant exposure of 10 Jcm^{-2} used in the actual clinical application an ablation rate of 60 μm per pulse. This is somewhat higher than the data given in Figure 2a. The difference could be caused by the larger spot size used in the present investigation, which reduces the possibility of water containing tissue fragments to escape from the beam path. As an additional factor we now found the repetition rate to play an important role on the ablation rate. The decrease of efficiency when the pulse frequency is enhanced might be due to scattering or absorption of the debris, which is the more accumulated in the beam path as faster the pulses follow each other. As a consequence, in clinical application with respect to the speed of skin removal a moved spot has to be preferred in order to reduce interference with the debris. This increases the ablation rates to values obtained for a fixed spot at lower repetition rates. Assuming an average ablation rate of 35 μm per pulse in the clinical application (10 Jm^{-2} $\emptyset = 2$ mm, $A = 3.1$ mm), the 580 pulses needed for 1 cm^2 of superficial tattoo removal will result in a total ablation depth of ~0.6 mm, which agrees well to the clinically observed exposure of the upper dermis along with an onset of capillary bleeding. Owing to the effective process of explosive tissue removal the amount of heat transferred to the adjacent structures is small. Consequently, we found coagulation zones not exceeding 30–40 μm at the bottom of the crater lesions. Our present in vitro study revealed a slight increase with repetition rate (up to ~50 μm) and no significant effect of pulse duration. However, in our clinical experience this narrow rim of heat necrosis was not thick enough to be hemostatic.

In clinical dermatosurgical use, a treatment spot size of 2 mm diameter required a pulse energy of ~320 mJ in order to achieve an efficient ablation at a radiant exposure of about 10 Jcm^{-2}. This parameter settings are currently provided by commercially available erbium:YAG laser equipment designed for dental surgery. A moved 2 mm laser beam spot applied at repetition rates of 5–10 Hz allows a controlled and quick ablation of larger lesions such as tattoos or epidermal nevi. Adjacent tissue coagulation at 10 Hz was not sufficient to prevent capillary bleeding or to produce a visible surface necrosis. For smaller punctual lesions, however, we preferred a 1 mm spot size. In our experience, this beam diameter offered an excellent control over ablative laser work. In papular adnexal and epithelial disorders, especially in delicate localizations such as the eyelid border (Fig. 3), pulsed erbium:YAG ablation was a safe and precise procedure. No unwarranted side effects were noticed after superficial skin ablation.

The procedure of Erbium:YAG skin ablation is comparable to a stepwise superficial dermabrasion with oozing of blood from capillary vessels. However, dermabrasion of larger areas is performed much quicker and bleeding of the abraded surface does not interfere with the ongoing surgery. Since the laser spot was moved during ablation, bleeding as a rule could be controlled until the laser beam reached the area again in the subsequent pass. Only in few cases with deeper lesions, the procedure was prolonged because intermittent compression was necessary until bleeding stopped. Therefore, whenever a rapid abrasion of a larger field is desired, dermabrasion should be considered instead of laser ablation. However, not all areas are equally well amenable to dermabrasion, especially delicate skin locations, such as in the periorbital or perioral region, where a precise, "nontouching" ablation should provide better control. In contrast, if one aims at a dry wound surface, carbon dioxide laser vaporization should be preferred. Also, the less coagulating flashscanned or ultrapulsed carbon dioxide laser systems currently used for skin resurfacing procedures still remove tissue hemostatically due to a greater depth of thermal injury, especially if additive pulses are used. For superficial skin resurfacing procedures the erbium laser should instead produce less thermal trauma than ultrapulsed carbon dioxide laser ablation and there is no need of removing the coagulated surface layer from the treated skin area, since in contrast to the latter erbium ablated tissue is ejected from the surface. In case a certain amount of tissue shrinkage usually associated with carbon dioxide laser resurfacing should be a prerequisite for a successful outcome of scar or wrinkle smoothening, this could result in less favorable result when using the erbium system.

With regard to the hazards of the procedure, Erbium:YAG laser ablation bears the same potential risks and side effects as dermabrasion for both the patients and the surgeon. These include

the risk of scar formation and of milia development especially with deeper lesions, of pigmentary changes, and also of infections. In deeper tattoos we therefore see no advantage over conventional dermabrasion, which might still become necessary in those selected cases that are neither amenable to surgical excision nor responding to selective photothermolysis. In order to avoid any hazards of contamination with potentially infectious ablated tissue material or splattered blood, the same precautions as in dermabrasion are advisable. Moreover, we used a smoke evacuator system to collect the tissue dust ejected from the ablated surface.

In summary, our present data support the view that pulsed midinfrared laser ablation with the Erbium:YAG system can be indicated in dermatosurgery, whenever a careful removal of superficial lesions (e.g., epidermal nevi), or of lesions in delicate locations (e.g., syringoma of the eyelids) is desired. Since a stepwise and highly precise ablation of the skin surface is possible without relevant tissue necrosis, a further promising indication should be all “skin resurfacing” procedures, especially in skin types prone to postinflammatory hyperpigmentation. In deeper lesions, however, the procedure might be complicated by the onset of interfering bleeding and bears the risk of scar formation. In those cases, dermabrasion should be advantageous, less time-consuming, and less expensive. The same holds true when considering the erbium:YAG system as a cutting device in cutaneous surgery, where in contrast to microsurgical procedures it will probably not offer an alternative to cold steel surgery or hemostatic electrosurgical devices.

ACKNOWLEDGMENTS

The authors thank Dr. R. Hartmann, Mr. K. Stock, Mrs. B. Moron, and Mrs. A. Böhmler for expert assistance.

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